Development of a Wireless, Commercial Electromyography System for Use in Athletics and Physical Therapy

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Abstract

Electromyography is a muscle activity recording technique that is not often used in a clinical setting due to difficulties in reproducibility. In this paper I aim to create a wireless, wearable system for electromyography. This system is built into a pair of compression shorts, and sends both electromyography and positional data from inertial measurement units to users' mobile devices. This system is primarily useful in physical therapy and athletic fields, as quantitative information on user gait can improve in the healing and training processes.

Introduction

Kinesiology, the study of body movement, is a field reliant on available data collection devices and tools. Motion tracking systems (Merletti, 2009), electrophysiological sensors (Rosenhahn, 2008), and positional sensors are just a few staple instruments used in clinical research. Electromyography (EMG), the measurement of the electrical signals driving muscles, is often used as a research tool for analyzing human movement (Alkner, 2000) and as a detector for neuromuscular disorders such as Parkinson's disease (Meigal, 2009). By correlating EMG readings to the force of muscular contraction, kinesiological researchers develop and refine models of human movement (Bogey, 1992). These models can correlate joint angles to muscle group recruitment, determine contact forces at joints, and describe the timing of muscle activation throughout motions. (De Luca, 1997).

Modeling human movement via EMG can provide great benefits, ranging from better understanding workplace injuries (Ferguson, 2005) to the development of functional prosthetic hands (Zhang, 2011). However, EMG data is not often directly utilized by consumers or outside of a clinical setting. Some efforts have been made to commercialize EMG systems, such as a Bluetooth enabled differential electrode (Youn, 2009). However, this and other similar devices use a single Bluetooth module for each stick-on electrode. Restricting each Bluetooth module to a single electrode requires each electrode to communicate independently with the central device, increasing the complexity of use. Furthermore, these stick-on electrodes are single use, and therefore must be replaced and repositioned with each use. The inconsistent nature of EMG readings also acts as a barrier to commercialization. Many factors can lead to decreased fidelity of an EMG signal, such as crosstalk between muscle groups, electrode positioning, blood flow, and the amount of fatty tissue between the electrode and the muscle (De Luca, 1997). These confounding factors reduce the ability of researchers to correlate EMG readings with quantitative measurements of the timing and force of muscular activation. However, by keeping the confounding factors in mind, EMG technology can be brought outside of clinical and research settings.

My research aims to accurately model femoral motion and muscle activation by creating a device that utilizes EMG and positional sensors for use outside of a clinical setting. Textile surface EMG (sEMG) electrodes will be used to measure the activation of major muscle groups, specifically the hamstrings and quadriceps as seen below in figure 1. Electrodes placed accurately on the middle of the muscle belly of large muscles are shown to minimize crosstalk (De Luca, 2012). Accurate repeated placement of the electrodes is ensured by sewing them into compression shorts, minimizing crosstalk in this device. By minimizing crosstalk, as well as transmitting data from a multi-electrode EMG system via a single Bluetooth module, this device solves the issues obstructing usage of EMG systems in a commercial setting. However, muscle activation of large muscle groups is not enough to fully characterize femoral motion. Inertial measurement units (IMUs) are used to supplement the EMG data with 6-axis positional data from an accelerometer and gyroscope. By integrating EMG and IMU data streams, a model of muscular activity and position of the femoral area can be created in real time. This model can

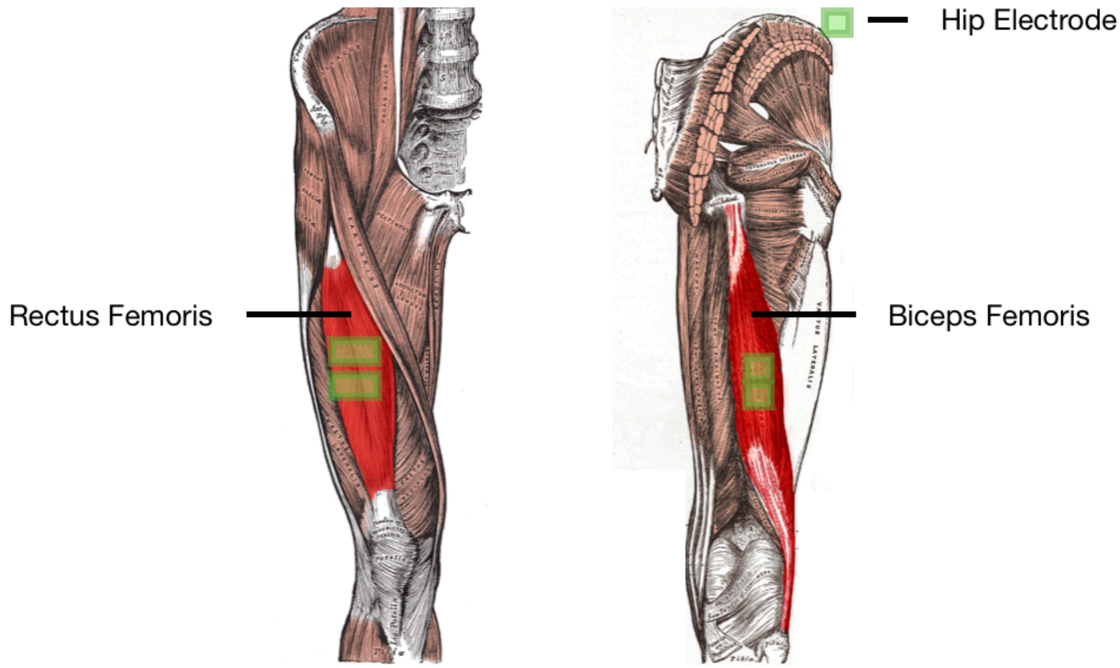

Figure 1. Textile EMG electrode locations on a right leg, indicated by green boxes. Muscle activity is recorded from the quadriceps rectus femoris (left) and hamstring bicep femoris (right). The hip electrode (right) is used as a ground reference, as there is little muscle present to generate a signal. Because these electrodes are sewn into compression shorts, they are placed accurately and consistently.

be applied to use for individuals in both athletic and rehabilitative fields, effectively diagnosing abnormalities in form and muscular activation.

No other device offers this level of functionality at a low cost. Devices at similar price points do not offer IMU support or multiple electrode configurations. Devices that offer IMU support can cost upwards of $1000 and are prohibitively expensive for use by consumers. By offering a wireless device that supports IMUs and multiple electrode configurations at a low price point, this technology can be offered to consumers for the first time.

Methodology

The device is comprised of three subsystems: hardware, electrical, and software. Furthermore, testing protocols for the electrical and software subsystems have been implemented.

Hardware

The hardware subsystem consists of the garment, in this case Nike compression shorts, and the circuit housings.

Compression Shorts

Two pairs of differential EMG electrodes, as well as a ground electrode, are sewn into each leg of the shorts in the locations seen in figure 1. Differential electrodes measure the difference in two electrical signals, reducing the noise common to each (Day, 2002). Each of these electrodes consists of a rectangle cut from Adafruit woven conductive fabric. Adafruit conductive thread is sewn to these electrodes and connects them to lead wires from the primary circuit board. The elasticity of the compression shorts ensures strong contact between EMG electrodes and the subject's skin. Maintaining this strong contact gives sEMG electrodes have similar efficacy to traditional EMG electrodes (Finni, 2007). Furthermore, the shorts' location on the body allows for placement of the textile EMG electrodes on femoral muscle groups. These muscle groups, the quadriceps and hamstrings, are some of the largest in the body, allowing for easy sEMG measurement. Two 9-axis MPU-9250 IMUs are sewn to the shorts on the lateral side of the thigh, providing a full positional model of femoral position. The position of each of these sensors can be seen in figure 1. This design is not limited to compression shorts or measurement of the femoral area. By using compression fabric to secure the EMG electrodes and IMUs, biomechanical data can be recorded from many muscle groups.

Circuit Housings

One of the primary uses of the lower body sensing system is analysis of movement during athletics. Exposed circuitry would have a high risk of damage, so circuit housings, as seen below in figure 2, were 3D printed and sewn to the compression shorts. These housings protect both the IMUs and the primary circuit board from physical and environmental damage.

Electrical

Figure 2. Circuit housings for the primary circuit board (left) and the IMU breakout boards (right).

The electrical subsystem consists of power circuits, an analog front end for EMG processing and digitization, and the Bluetooth radio with an included ARM processor.

Power

The power circuitry drives three voltages: 3.6V, 5V, and -5V. The 3.6V output is driven by the battery charging circuit. This circuit routes a 5V input from a micro USB port to the battery charging chip BQ24297RGET. This chip charges a 3.6V lithium ion battery and regulates the output voltage to a constant 3.6V. This output voltage is used to drive digital components, such as the bluetooth radio and the IMUs. The 3.6V output is boosted to 7.2V and -7.2V by the power regulation chip MAX680, and these voltages are regulated to 5V and -5V by the power regulation chips MAX666 and MAX664 respectively. These voltages are used to power the operational amplifiers in the EMG analog front end.

EMG Analog Front End

The EMG analog front end filters and digitizes the EMG data. To avoid implementing a front end for each electrode, a pair of MAX4734 multiplexers routes a pair of differential EMG signals to the front end during each sampling event. This reduces the maximum sample rate by a factor of the number of EMG electrodes implemented, in this case four. Despite this reduction, the sampling rate of the ARM processor’s analog to digital converter is sufficiently high to capture spectral information within EMG band, from 10 to 100 Hz (Merletti, 1999). Using a single front end reduces the size and cost of the device. After passing through the multiplexer, the differential EMG signal passes through an INA128 instrumentation amplifier, reducing the signals to a single differential voltage and stepping the voltage up to a usable value. This differential voltage then passes through a bandpass filter from 15 to 130 Hz consisting of two UA741 operational amplifiers, minimizing spectral information outside of the EMG band. The signal is then digitized by the analog to digital converter and processed by the ARM processor.

Software

The software subsystem has two main components: the peripheral component within the Bluetooth module and the central component within the mobile device.

Bluetooth Module

The nRF52832 Bluetooth module contains an ARM processor, which performs basic data analyses, connects to the mobile device, and modifies the settings of adjustable components such as the battery charging chip. Bluetooth was selected over other communication protocols due to its compatibility with mobile devices. Upon an EMG sampling event, each of the four differential electrodes are sampled sequentially. These signals are then compiled into a packet and transmitted to the mobile device. Unlike the EMG sensors, the IMUs communicate with the ARM processor via I2C. Data registers are converted into accelerometer, gyroscope, and magnetometer data by the MPU9250 open source library developed by Kris Winer. A packet consisting of accelerometer, temperature, and gyroscope data is transmitted to the mobile device upon each sampling event.

React Native Mobile Application

The mobile application was developed in javascript using the React Native framework. React Native was selected over other development systems due to its compatibility with both Android and iOS, as well as its extensive open source libraries.

Bluetooth Peripheral Interface

React-native-ble-plx, an open source library developed by Polidea, was utilized to communicate with the Bluetooth peripheral device. Data is displayed to the user as it is being transmitted and concurrently saved to the SQLite database.

SQLite Database

The SQLite database framework is incorporated into react native by the open source library react-native-sqlite-storage, developed by Andrzej Porebski. The SQLite database consists of a single data table with four columns: ID, time stamp, value, and type, which may be either EMG, IMU, or battery.

User Interface and Navigation

The react-native-material-ui library developed by Xotahal is used to maintain consistent style throughout the application. Furthermore, this is the default theme for Android applications. This will make application usage and navigation intuitive for most users. The react-navigation library allows for transitions between screens.

Data Processing

The streams of IMU accelerometer and gyroscopic data are converted into roll, pitch, and yaw for each leg of the device using Kris Winer's open source MPU9250 library. A 7 point sliding window is used to compute average EMG signal power, and spectral power is computed using the fast Fourier transform (FFT). EMG signal power is used quantify the amount of activity in a muscle, whereas the information from the IMUs is used to analyze motion.

Testing Protocols

Electrical Testing

To ensure fidelity of the EMG Analog front end, a frequency sweep was run through its input and the gain and phase shift at the output was recorded. Plotting these values against frequency shows the frequency response of the bandpass filter, ensuring properly scaled EMG data is recorded. Voltage levels at the output of power regulation devices and the battery are also recorded using a digital multimeter to ensure sustained component integrity. The voltage levels to be recorded can be seen below in Table 1.

Table 1. Circuit Board Expected Voltage Levels

Voltage Level	Measured Voltage
Battery Voltage (Full Charge)	3.7 V
Regulated Battery Voltage	3.7 V
MAX680 Output (+)	7.2 V
MAX680 Output (-)	-7.2 V
Postive Operational Amplifier Supply	5 V
Negative Operational Amplifier Supply	5 V

System Testing

In order to test the system as a whole, a subject will perform a slow, deep squat. The deep squat was selected as a calibration procedure because both hamstrings and quadriceps forces will be at a maximum at a knee angle of approximately 55 degrees (Dahlkvist, 1982). The biomechanical model will be constructed and normalized between individuals to establish calibration values. Furthermore, recordings and representations will be made of both positional and EMG data captured during standard gait.

Budget

Production cost for a single prototype device is $454. Assembly cost was calculated for a four-hour assembly time at $20 per hour. The cost of the circuit board and electrical components will drop to as low as $40 at scale, bringing production cost to $186. Further reductions in assembly time as well as development of a proprietary IMU board will also lower costs.

Table 2. Itemized and Total Cost of Device.

Item	Cost
Nike Compression Shorts	$22
Adafruit Woven Conductive Fabric	$6
Adafruit Conductive Thread	$8
Inertial Measurement Unit (x2)	$30
Circuit Board	$215
Electrical Components	$93
Device Assembly	$80
Total	$454

Results

Electrical Testing

The frequency response of the analog front end bandpass filter can be seen below in Figure 3. The cutoff frequencies of the bandpass filter were found to be 33 and 620 Hz, with a midband gain of .8dB. The lower cutoff frequency must be brought down to 10 Hz, and the upper cutoff frequency must be brought down to 100 Hz. The current filter will allow for a noise analysis of EMG signals upon device completion This analysis will determine whether common noise, such as at 60Hz, should be reduced by an analog device.

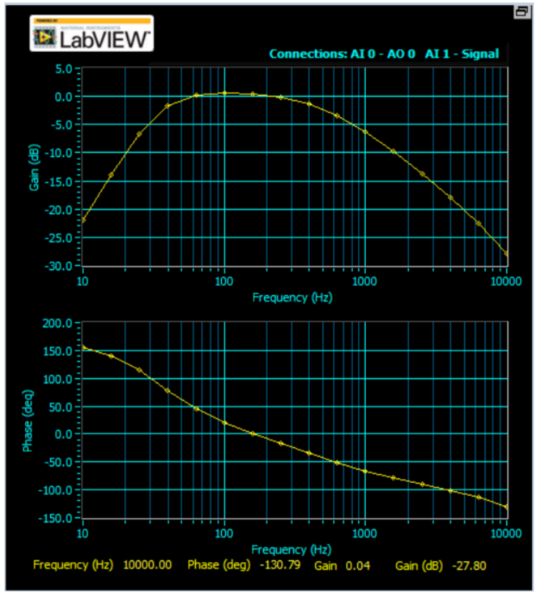

Figure 3. Analog front end filter frequency response.

Table 3. Circuit Board Measured Voltage Levels

Voltage Level	Measured Voltage
Battery Voltage (Full Charge)	3.742 V
Regulated Battery Voltage	3.742 V
MAX680 Output (+)	7.188 V
MAX680 Output (-)	-6.769 V
Postive Operational Amplifier Supply	5.061 V
Negative Operational Amplifier Supply	-4.998 V

Circuit board voltage levels may be seen above in Table 3. All regulated voltages are within 1.5% of the expected values, confirming that the device is operating safely.

System Testing

IMU data was recorded for a single individual with standard gait during one pace. Due to the slow transmission speed over bluetooth, this data was recorded over a wired connection, preventing EMG measurement. The IMUs' roll, pitch, and yaw were exported to MATLAB. Plots of this data may be seen below in Figure 4. High amplitude, high frequency spikes in position are indicative of impacts from both the ipsilateral and contralateral foot. Computation of the positional signals' power spectral density (PSD) allows for detection of these impacts. When the PSD is 20dB greater than the local average one second in either direction, an impact is detected. This data was recorded on an earlier prototype, and due to transmission speed issues with the Bluetooth peripheral device, the calibration procedure was not recorded.

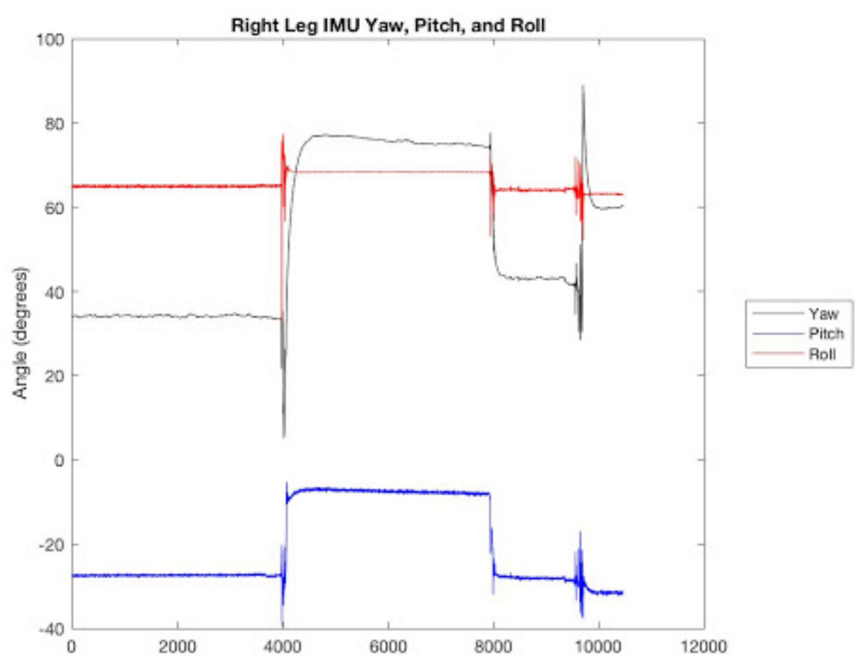

Figure 4. Right quadriceps IMU roll, pitch, and yaw for a single pace. High amplitude spikes in the position occur during the heel strike and toe off phases of gait, and are used to separate individual paces for analysis.

Mobile Application Navigation and Usage

The mobile application initially loads the user to the home screen as seen in Figure 5(a). This page provides some basic app navigation information to the user. From here, the user will typically navigate to the devices page, seen in Figure 5(b), to begin a recording session. The Scan button connects the app to the compression shorts via Bluetooth. Data is displayed on the devices screen and sent to the SQLite database as it is recorded. The stop scan button pauses the connection between the compression shorts and the mobile application, while the disconnect button ends the pairing between the compression shorts and the mobile application. After performing a recording, data can be viewed on the recorded data screen, seen in figure 5(c). While recordings can be performed, data transmission currently occurs below 32 bytes per second. This prevents in depth analyses of motion. However, this is a limitation of the software rather than the hardware. Further development will result in faster transmission speeds.

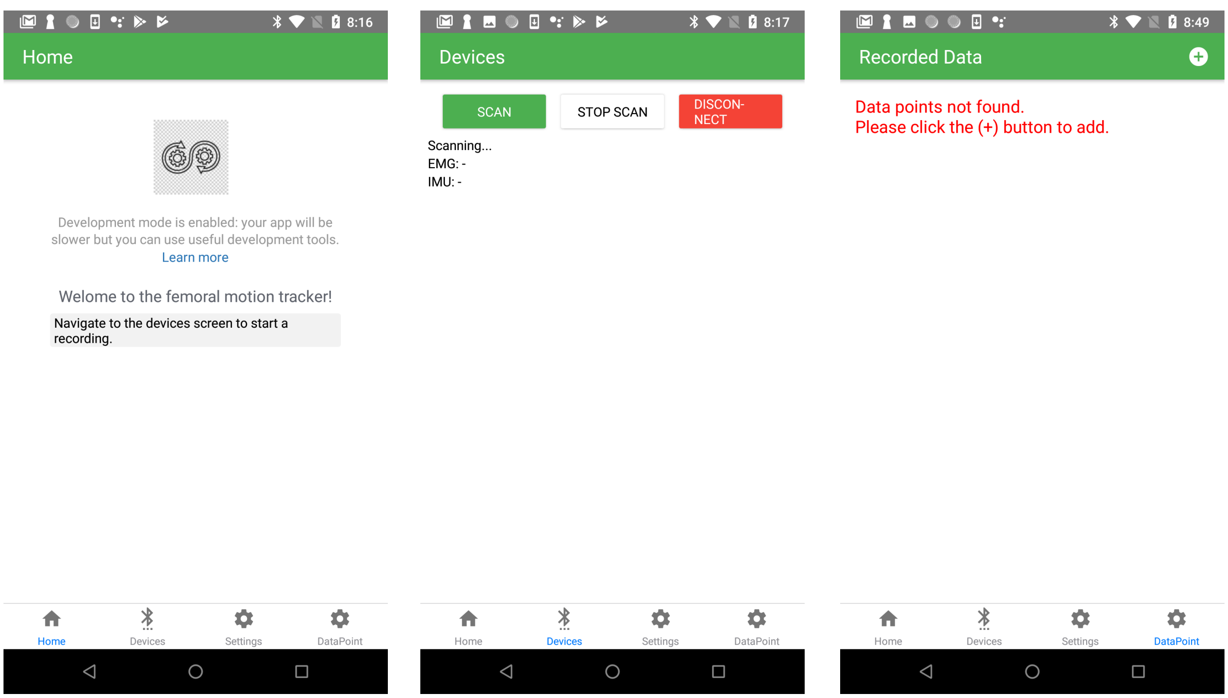

Figure 5. Home screen (a), device recording screen (b), recorded data screen (c).

Data points can be viewed, added, and edited from the recorded data screen, as seen in figure 6(a,b,c). The add and edit features are only available in developer mode and are used to test database structure and functionality.

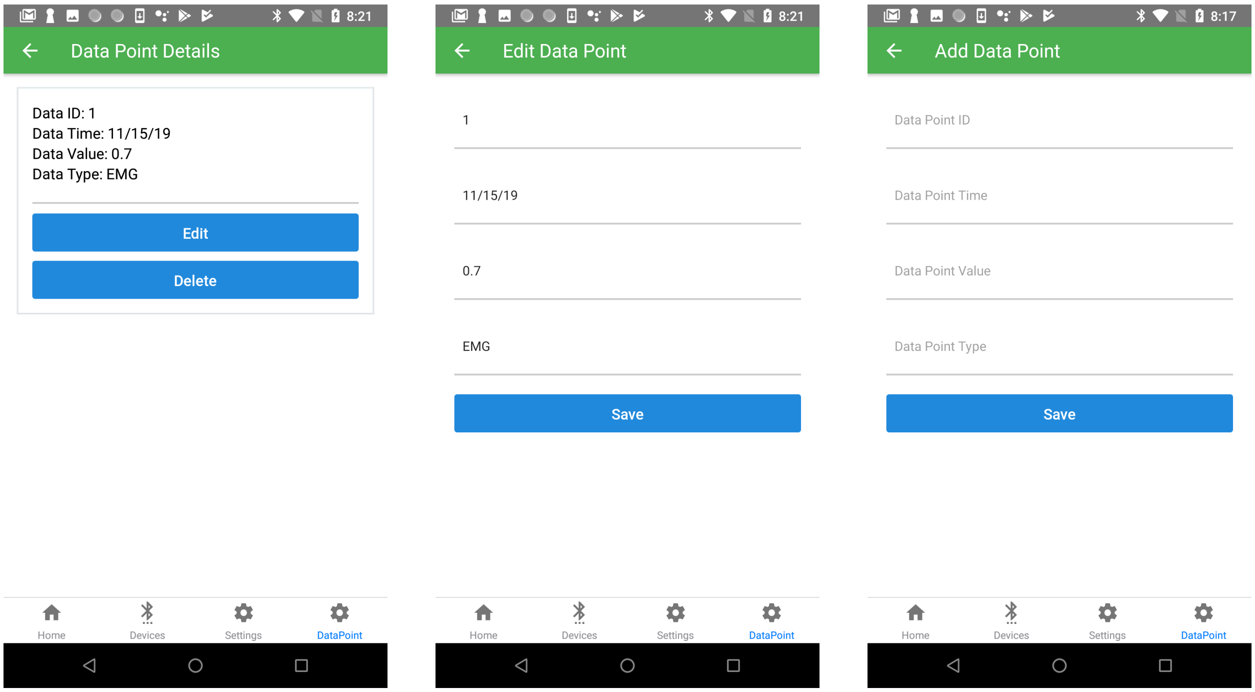

Figure 6. Data point details screen (a), data point edit screen (b), add data point screen (c).

Discussion

This wearable sensor, by combining EMG and IMU data, will be able to provide useful analytics for use in athletics and physical therapy. Functionality of individual sensors in the device was verified during system testing. Furthermore, the electrical testing verified that the circuit board operates. However, the data transmission rate between the peripheral Bluetooth radio and the mobile application is too small to perform meaningful analyses. This is a limitation of the peripheral Bluetooth device's software, therefore further developments may solve this problem. Once the mobile application is capable of recording and presenting data in real time, discussions with potential clients will be applied to the design of custom analyses for the various applications of this system.

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